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ANALYTICAL STUDY ON SEISMIC BEHAVIOR OF URM HOLLOW BRICK HOUSES RETROFITTED USING FERROCEMENT LAYERS

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ABSTRACT: Many simple residential buildings constructed with unreinforced masonry (URM) hollow bricks were notably damaged during the 2022 West Pasaman Earthquake in Indonesia. URM buildings face a significant risk of lateral loads during earthquakes due to their low ductility and tensile strength. One way to retrofit these URM hollow brick houses is using the ferrocement layer method. This study focuses on an analytical study of seismic behavior on a typical URM hollow brick house in West Pasaman damaged by the 2022 West Pasaman Earthquake, which was retrofitted using the ferrocement layer method. In this analytical study, two simple URM hollow brick house prototypes commonly found in West Pasaman were analyzed: an original URM hollow brick house and the URM hollow brick house retrofitted with ferrocement layers. Four variations of time history earthquake acceleration loads were applied to these models: 0.3 g, 0.6 g, 1.0 g, and 1.5 g. The tensile stress pattern on the walls of a retrofitted URM hollow brick house model across different earthquake acceleration scenarios is compared to that of the original URM hollow brick house model. The analytical results show that retrofitting a URM hollow brick house with ferrocement layers not only enhances the walls' strength but also diminishes tensile stress levels. The capacity of the URM hollow brick house improves by 70% when it is retrofitted using ferrocement layers. So, the URM hollow brick houses with ferrocement layers will be safe against earthquakes.

Keywords: URM Houses, Hollow Brick, Earthquake, Retrofitting, Ferrocement Layers

1. INTRODUCTION

Unreinforced Masonry (URM) is often chosen in building construction by communities in Indonesia with low economic conditions. The vulnerability of URM structures to seismic events is a significant concern, particularly in regions prone to earthquakes.

Earthquakes that frequently occur in almost all parts of Indonesia cause a lot of damage to URM buildings such as the West Pasaman Earthquake in 2022, which resulted in extensive damage to basic residential buildings lacking reinforcing components [1]. URM buildings face a significant risk of lateral loads during earthquakes due to their low ductility and tensile strength [2-5]. In Indonesia, a considerable portion of simple URM houses made of unreinforced hollow brick walls fail to meet construction standards due to financial limitations, issues with building materials, lack of skilled builders, and overall poor construction quality [6-8]. It is essential to highlight that the primary cause of life and property loss during earthquakes is often attributed to the collapse of these inhabited structures [9-11].

Numerous investigations have been carried out regarding the behavior of URM structures during earthquakes, such as Performance of Unreinforced Masonry Walls in Compression [12], Experimental diagonal tension (shear) test of Un-Reinforced Masonry (URM) walls strengthened with textile reinforced mortar (TRM) [13], Shaking table study on the seismic performance of an Iranian traditional Un-Reinforced Masonry (URM) building [14], and Experimental Study on the Retrofitting of Damaged Hollow Brick Masonry using a Ferrocement Layer [15].

Fig.1 URM hollow brick house damage due to the 2022 West Pasaman Earthquake

In 2022, the West Pasaman earthquake, with a magnitude of 6.2 Mw, damaged the community's houses, most of which were built using unreinforced hollow brick masonry (URM) and were heavily damaged, as shown in Fig. 1. Brick materials have the characteristics of being heavy and brittle, and they have almost no ductility. Therefore, These URM houses pose a significant danger to individuals because they are susceptible to sudden collapse during earthquakes [16].

Understanding the seismic behavior of these structures and implementing effective retrofitting measures are imperative for enhancing community resilience and minimizing the devastating impact of seismic events. Retrofitting using the ferrocement layers method is an effective retrofitting method compared to other retrofitting methods [17]. The method of retrofitting ferrocement layers is cheap, the materials are easy to find, and the installation is not complicated [18]. Hence, it is more possible for the community to retrofit their residential buildings independently.

This study focuses on an analytical study of a typical Unreinforced Masonry (URM) house damaged by the 2022 West Pasaman Earthquake, which was retrofitted using the ferrocement layer method.

2. RESEARCH SIGNIFICANCE

The destructive earthquake resulted in significant damage to many Unreinforced Masonry (URM) community houses, making it necessary to retrofit these houses, one of which is using ferrocement layers. In this research, finite element analysis was carried out to determine the seismic behavior of an original URM house, which is compared with the URM house retrofitted using ferrocement layers. This study is very important, as the results can be used as a reference in building earthquake-safe houses in earthquake-prone areas, both in disaster mitigation efforts and at the post-earthquake reconstruction stage.

3. ANALYTICAL WORK

3.1 URM House Models

In this analytical study, two simple URM hollow brick house prototypes commonly found in West Pasaman were analyzed: one original URM house and one URM house retrofitted with ferrocement layers, as depicted in Figs. 2-5. Both model houses have the same dimensions of 1.5 m x 1.5 m x 1 m, which is scaled 1:4 from their original size. The simple house modeled in this study is a type of community hollow brick house in West Pasaman with a size of 600 cm x 600 cm x 400 cm. The retrofitting of the URM house model using ferrocement layer was conducted by installment of woven wire covered by concrete mortar.

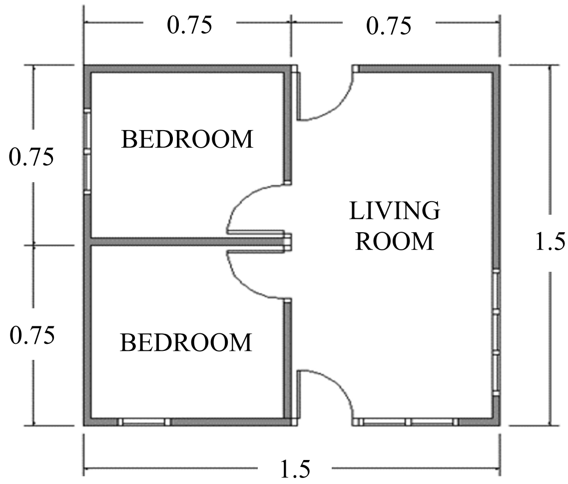


Fig.2 Plans for the model house without retrofitting

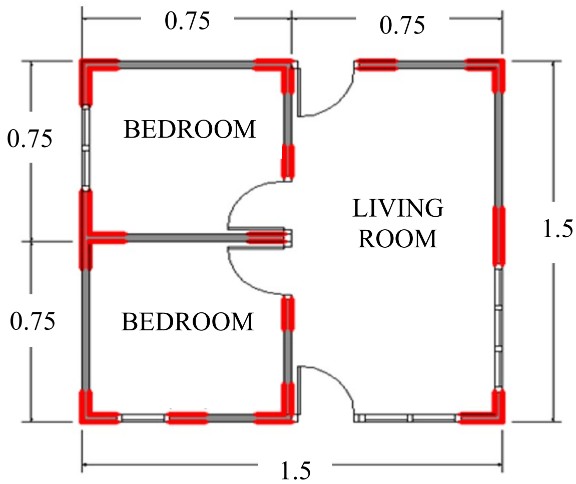


Fig.3 Plans for the model house retrofitted using a ferrocement layer

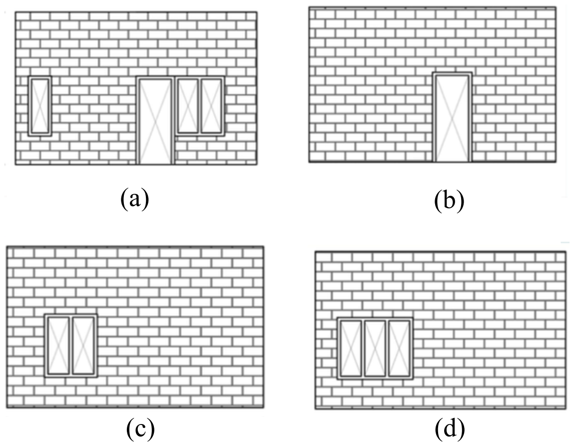


Fig.4 Model house without retrofitting; a) front view, b) back view, c) left side view, and d) right side

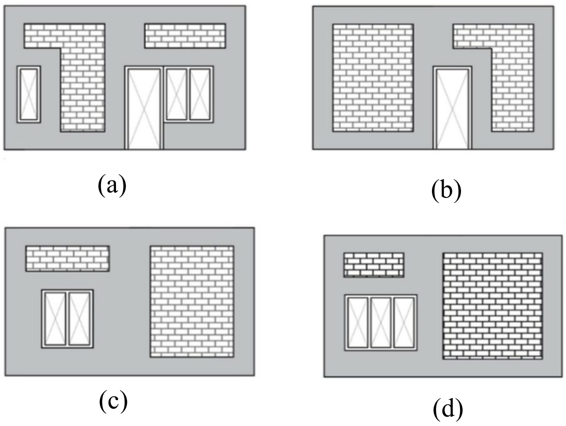


Fig.5 Model house with retrofitting; a) front view, b) back view, c) left side view, and d) right side

The construction process for the retrofitted URM hollow brick house consists of several stages, starting from wall construction (Fig. 6), followed by installing woven wire with concrete nails and concrete tie wire on both sides of the wall (outside and inside), as shown in Fig. 7. Then, plaster the wall using cement mortar (cement-sand mixture) in the area where the woven wire is installed (covering the installed woven wire) (Fig. 8). The retrofitted model URM house is illustrated in Fig. 9.

Fig.6 Model house making process

Fig.7 Woven wire installation process

Fig.8 Plastering process of the wall covering the installed woven wire

Fig.9 The retrofitted model URM house

3.2 Material Properties

In this study, three materials are defined: hollow brick material, concrete mortar, and woven wire (defined as steel).

The hollow brick has a compressive strength (fc') of 2.5 MPa, a shear modulus of 3096 MPa, a modulus of elasticity of 7431.35 MPa, and a specific gravity of 1600 kg/m^3. Plaster has a compressive strength (fc') of 9.9 MPa, a shear modulus of 6161.75 MPa, a modulus of elasticity of 14788.2 MPa, and a specific gravity of 1600 kg/m^3. Woven wire has a yield strength (fy) of 275 MPa, ultimate tensile strength (fu) of 620 MPa, shear modulus of 187500 MPa, and a specific gravity of 8.0 g/cm^3 [19].

3.3 Modeling

The URM hollow brick houses were modeled using the finite element method (ETABS V21), as shown in Figs. 10 and 11. Fig. 10 illustrates a URM house model, with the walls defined as hollow brick walls with specific data properties.

Meanwhile, Fig. 11 depicts a house model with ferrocement layer retrofitting. The red color represents the wall area without retrofitting, defined as a hollow brick wall with data properties (Fig. 12). The blue color represents the wall area that has been retrofitted, defined as a wall consisting of five layers. Data properties for the retrofitted wall area (Fig. 13).

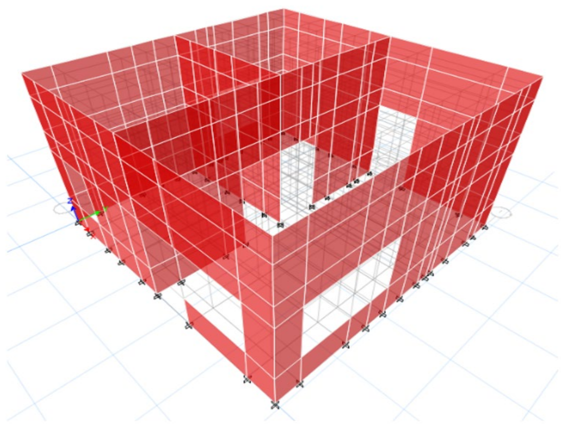


Fig.10 Modeling of the original URM house

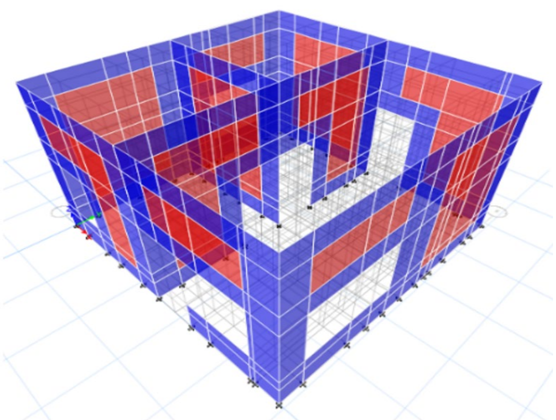


Fig.11 Modeling of the URM house retrofitted using ferrocement layer

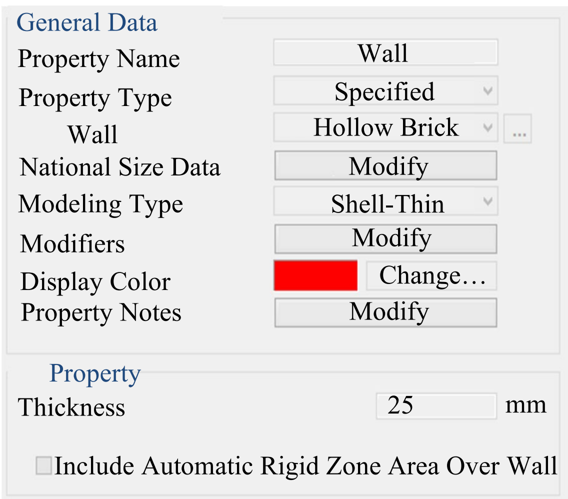
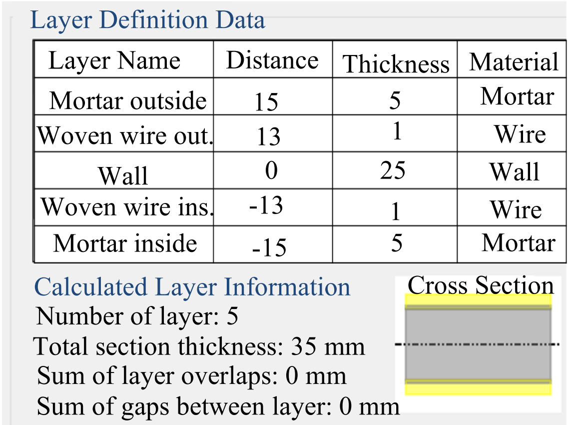


Fig.12 Wall property data of URM hollow brick house



Layer Definition Data

Layer Name	Distance	Thickness	Material
Mortar outside	15	5	Mortar
Woven wire out.	13	1	Wire
Wall	0	25	Wall
Woven wire ins.	-13	1	Wire
Mortar inside	-15	5	Mortar

Calculated Layer Information
Number of layer: 5
Total section thickness: 35 mm
Sum of layer overlaps: 0 mm
Sum of gaps between layer: 0 mm

Fig.13 Wall property layer definition data of the URM house retrofitted using ferrocement layers

3.4 Loading Analysis

Table 1 Weight of model house

Material	Weight (kg)
Hollow brick	157
Mortar	246
Weight of roof frame and roof	68
Total weight of model house	471

Table 2 Weight of the original house

Material	Weight (kg)
Hollow brick	10606
Mortar	4172
Weight of roof frame and roof	718
Total weight of original house	15496
qa: Dead load weight of the original house	430 kg/m^2

The loading was conducted by converting the weight of the original house to the model based on the area scale [20]. The model house weighs 471 kg, as shown in Table 1. The original house, without being scaled, weighs 430 kg/m^2, as presented in Table 2. Therefore, an additional load is needed based on the weight scale of the model house, which is calculated using the following Eq. (1):

$$Ls \times qa = qs \quad (1)$$

where, Ls: area of model house (m^2), qa: heavy house original (kg/m^2), qs: weight scale of model house (kg).

so,

$$2.25 \text{ m}^2 \times 430 \text{ kg/m}^2 = 968 \text{ kg}$$

Therefore, an additional load of 500 kg is applied to the model house. The value is derived from the difference between the calculated weight of the model house based on the area scale and the house model weight. This extra load is distributed into 9 points in the model houses, as illustrated in Fig. 14.

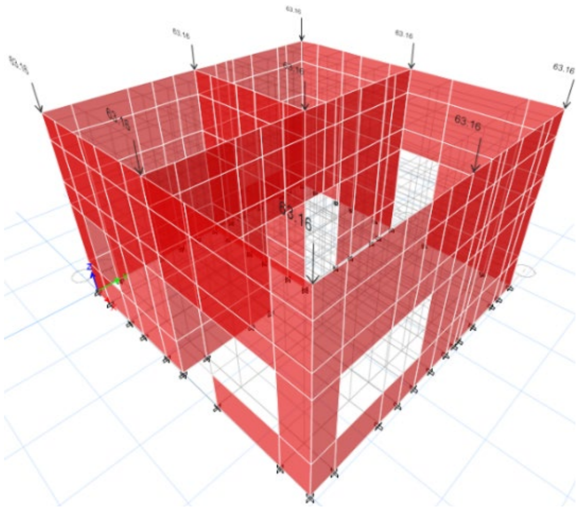


Fig.14 Additional dead loads on model houses

3.5 Numerical Analysis

In this study, the numerical analysis was carried out using ETABS V21 with the time history of earthquake loads. The time history from variations in earthquake frequency of Padang City, Indonesia. Four variations of earthquake acceleration loads were applied: 0.3 g, 0.6 g, 1.0 g, and 1.5 g, each with a duration of 30 seconds.

4. RESULTS AND DISCUSSION

4.1 The Behavior of Model Houses at 0.3 g Earthquake Acceleration

The results of finite element method analysis at an earthquake acceleration of 0.3 g are illustrated in Figs. 15 and 16. Fig. 15 depicts the stress pattern of the original URM house, while Fig. 16 displays the stress pattern on the house retrofitted using ferrocement layer method. It can be observed from the figures that the stress occurring on the walls of the house is predominantly represented by yellow and green stresses, both for the URM house (Fig. 15) and the retrofitted house (Fig. 16). The stress in yellow and green indicates tensile stress. The highest tensile stress is found in the opening areas, especially in the largest room, namely the living room. The maximum tensile stress in the URM model house reaches 2.17 MPa, surpassing the tensile strength of the hollow bricks, which is 0.20 MPa, as per Eq. (2) [21].

$$f_r = 8\% \, f_c' \qquad (2)$$

$$f_r = 8\% \times 2.5 = 0.20 \text{ MPa}$$

Where f_r = Tensile strength (MPa); f_c' = Compressive strength of hollow brick (MPa).

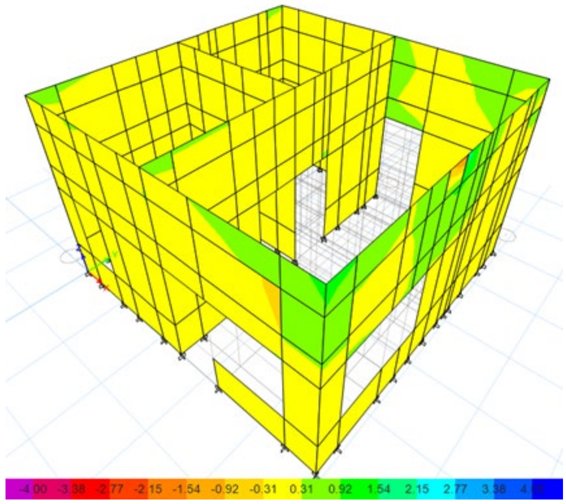


Fig.15 Wall stress patterns on URM house walls due to an earthquake acceleration 0.3 g

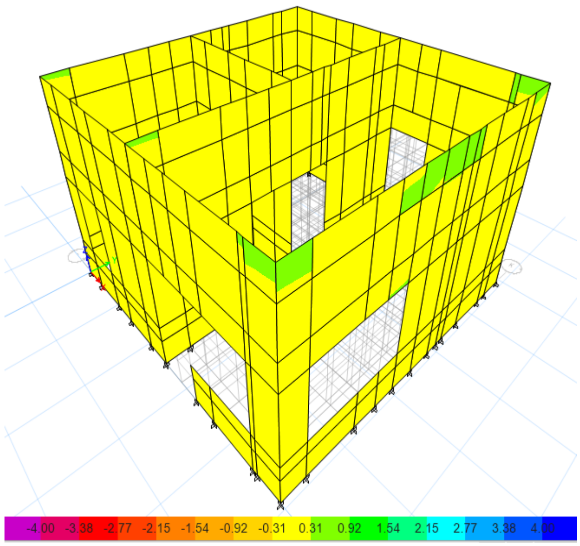


Fig.16 Wall stress patterns on URM house walls with retrofitting at acceleration earthquake 0.3 g

With the tensile stress exceeding the strength of the hollow brick, there is a significant risk, and the likelihood of wall damage or even collapse is high due to the absence of a reinforcing component. On the other hand, the model house that underwent retrofitting exhibited a maximum tensile stress of 0.65 MPa, surpassing the tensile strength of the concrete blocks (0.20 MPa). Despite the tensile stress exceeding the tensile strength of the hollow bricks, the using of ferrocement layers in the retrofitting process suggests that the wall is less likely to sustain damage. It is attributed to the presence of woven wires within the ferrocement layer, providing high tensile strength.

4.2 The Behavior of Model Houses at 0.6 g Earthquake Acceleration

Based on the analysis results, the dominant stress observed is tensile, as illustrated in Figs. 17 and 18. The highest tensile stress is concentrated in the opening area, particularly the living room. Compared to these figures, it is found that houses reinforced with a layer of ferrocement (Fig. 18) have lower pressure than houses without retrofitting (Fig. 17). The maximum pressure of a house retrofitted with a layer of ferrocement is 0.9 MPa, which increased by 0.25 MPa from the previous results. Despite surpassing the strength of hollow brick, walls are less susceptible to collapse due to the retrofitting provided by the ferrocement layer. In contrast, in houses without retrofitting, the maximum tensile stress reaches 1.9 MPa, posing a risk of wall collapse due to the absence of retrofitting components.

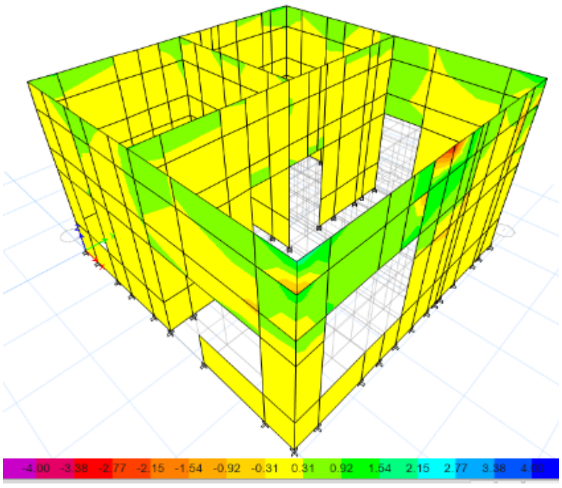


Fig.17 Wall stress patterns on URM house walls due to an earthquake acceleration 0.6 g

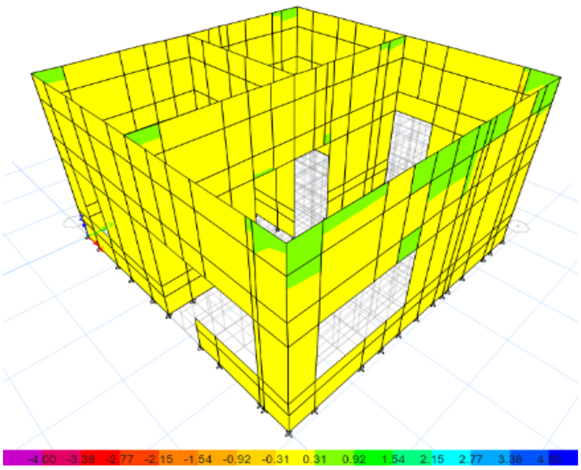


Fig.18 Wall stress patterns on URM house walls with retrofitting at acceleration earthquake 0.6 g

4.3 The Behavior of Model Houses at 1.0 g Earthquake Acceleration

The analysis results at an earthquake acceleration of 1.0 g are presented in Figs. 19 and 20. Fig. 19 illustrates the stress pattern on the wall of the house without retrofitting, while Fig. 20 displays the stress pattern on the wall of the house with retrofitting. These figures reveal that the stress on the walls of the unreinforced house is higher than on the walls of the house retrofitted with ferrocement layers. It is evidenced by the presence of blue stress and green stress in the original URM house, both of which are greater than the corresponding stresses in the ferrocement layer retrofitted house. The blue stress ranges from 1.55 MPa to 3.80 MPa, the green stress ranges from 0.31 MPa to 1.54 MPa, and the yellow stress ranges from 0 to 0.31 MPa.

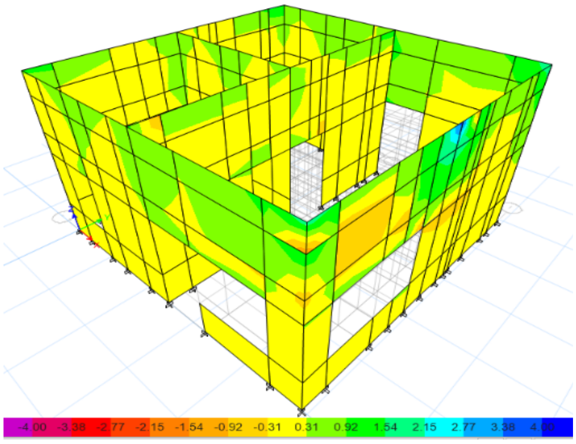


Fig.19 Wall stress patterns on URM house walls due to earthquake 1.0 g

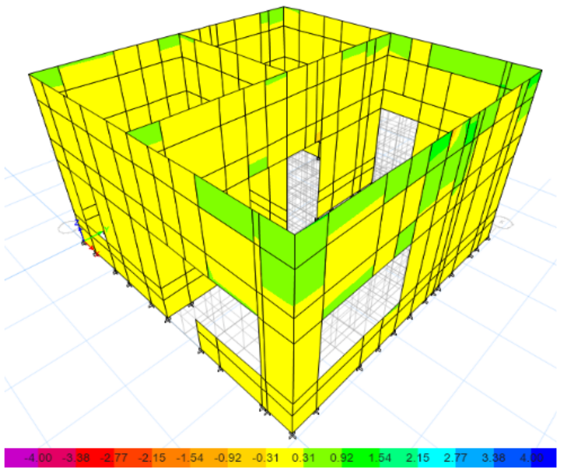


Fig.20 Wall stress patterns on URM house walls with retrofitting at acceleration earthquake 1.0 g

The maximum tensile stress on the walls of a house retrofitted with ferrocement layers is 1.3 MPa, whereas on the walls of the house without retrofitting, the maximum tensile stress reaches 3.8 MPa.

4.4 The Behavior of Model Houses at 1.5 g Earthquake Acceleration

The analysis results at an earthquake acceleration of 1.5 g are depicted in Figs. 21 and 22. Fig. 21 illustrates the stress pattern on the walls of an original URM house, while Fig. 22 displays the stress pattern on the walls of the house with retrofitting. The maximum tensile stress occurring on the walls of the house retrofitted with ferrocement layers (1.6 MPa) is smaller than the maximum tensile stress on the walls of the house without retrofitting (3.10 MPa).

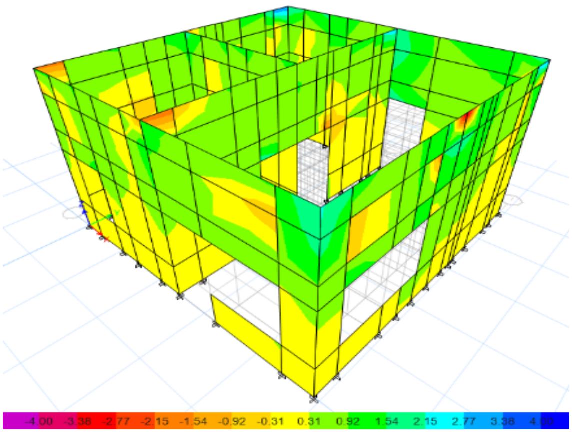


Fig.21 Wall stress patterns on URM house walls due to earthquake acceleration 1.5 g

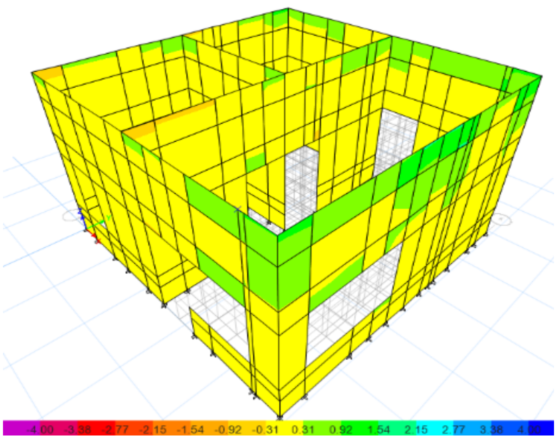


Fig.22 Wall stress patterns on URM house walls with retrofitting at acceleration earthquake 1.5 g

These results suggest that, apart from enhancing the strength of the walls, reinforcing a house with ferrocement layers can also mitigate the tensile stress occurring on the walls.

5. CONCLUSIONS

Based on this study, it can be concluded that the maximum tensile stress that occurs on the wall of the model house in all variations of acceleration, both URM and retrofitted URM model houses, exceeds the tensile strength of the hollow brick. However, in a model house retrofitted with ferrocement layers, it is unlikely that damage will occur because, in the ferrocement layer, there are woven wires with high tensile strength, which can increase the capacity of the wall. Meanwhile, the original URM model house will most likely experience damage due to low ductility and tensile strength.

The tensile stress that occurs in a URM hollow brick model house with ferrocement layers retrofitted in all variations of earthquake acceleration is smaller than that in a URM hollow brick model house without retrofitting. The capacity of the URM hollow brick house improves by 70% when it is retrofitted using the ferrocement layer. These results indicate that the ferrocement layer contributes to not only increasing the strength of the wall but also reducing the stress that occurs so that the retrofitted houses are safe against earthquakes.

6. ACKNOWLEDGEMENTS

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